Photon production from gluon fusion in heavy-ion collisions

Alejandro Ayala*, J. Castaño-Yepes,
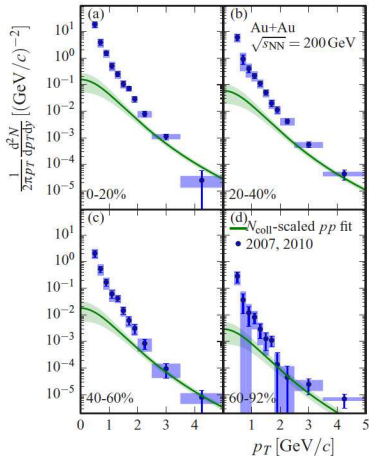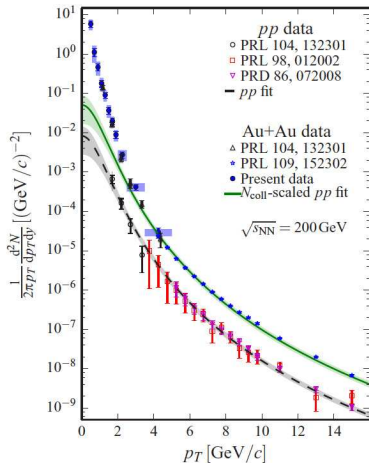C. A. Dominguez, L. Hernández

(*) Instituto de Ciencias Nucleares, UNAM
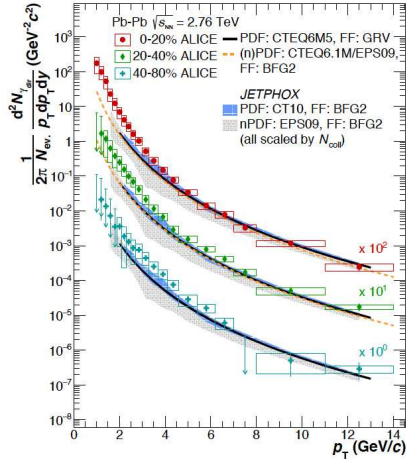
ayala@nucleares.unam.mx

11th international workshop on High-pT Physics in the RHIC & LHC Era, BNL April 2016

PHENIX, Phys. Rev. **C** 91, 064904 (2015)

ALICE, Phys. Lett. B **754**, 235-248 (2016)

Outline

- Thermal photon excess as of 2014
- Current status: Data vs. models
- Magnetic field effects as a source of excess yield
- Gluon fusion into photons
- Conclusions

PHENIX compared to models as of 2014: Yield underestimated

- ▶ Transport model: Linnyk, Cassing, Bratkovskaya, Phys. Rev. **C** 89, 034908 (2014)
- ▶ Fireball model: van Hees, Gale, Rapp, Phys. Rev. **C** 84, 054906 (2011)
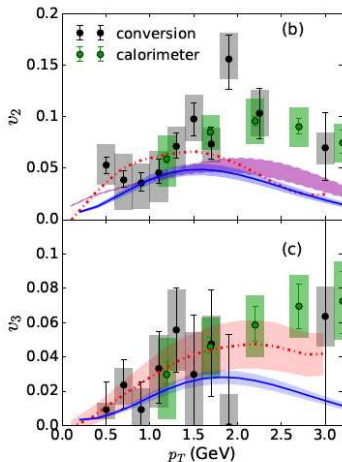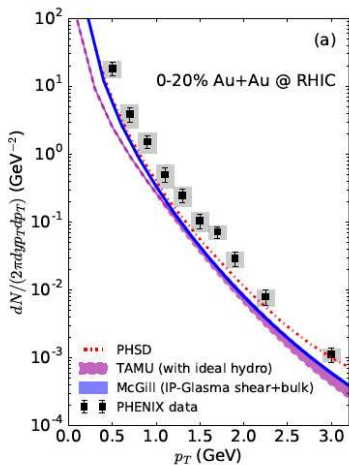- ▶ Hydro model: Shen, Heinz, Paquet, Gale, Phys. Rev. **C** 89, 044910 (2014)
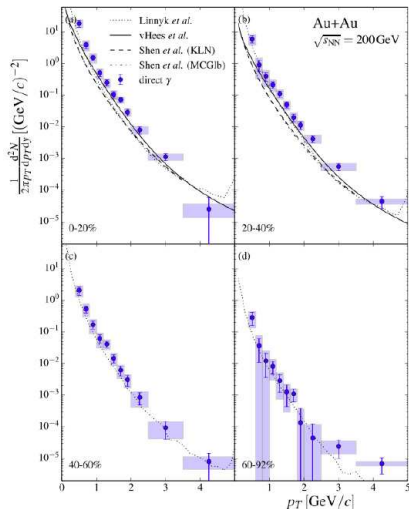
PHENIX compared to models as of 2014: Yield underestimated
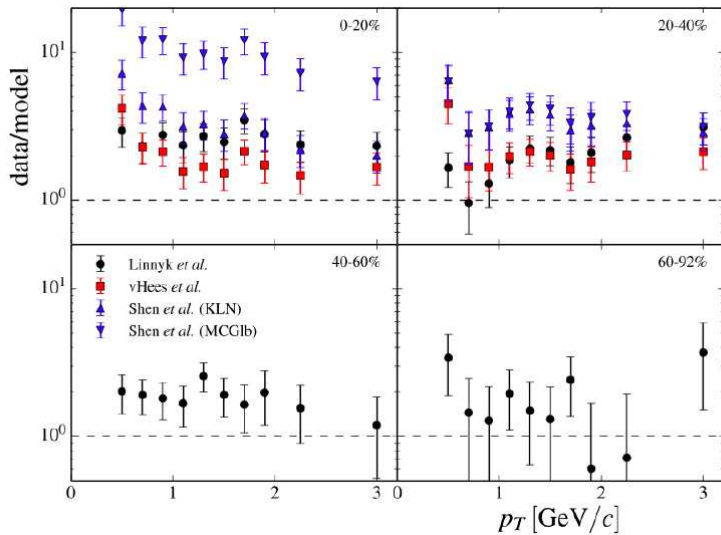
PHENIX compared to models as of 2016: improvement
C. Shen e-Print: arXiv:1601.02563

J.-F- Paquet *et al.*, arXiv:1509.06738
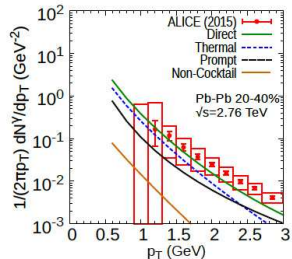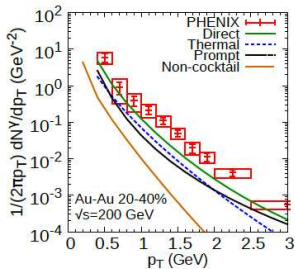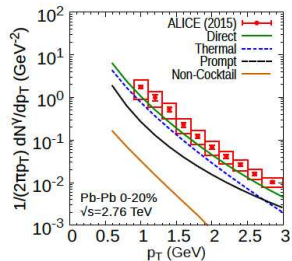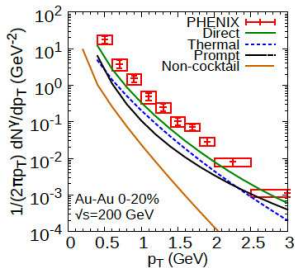
Summary of photon excess yield and flow:

- Models have improved (including updated photon emission rates, viscosity, IP-Glasma)
- Models consistent with yield within the **(lower part of)** uncertainties
- v_2 still not well described
- v_3 better described than v_2

Magnetic field in heavy-ion collisions
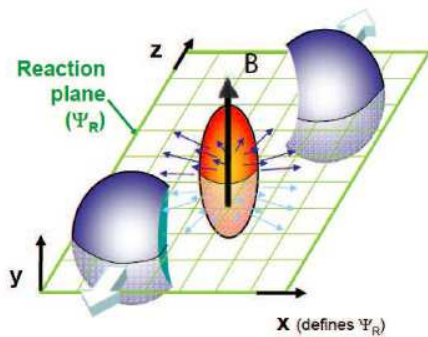
Charge separation along the magnetic field

W. Broniowski, W. Florkowski, Phys. Rev. **C** 65, 024905 (2002)
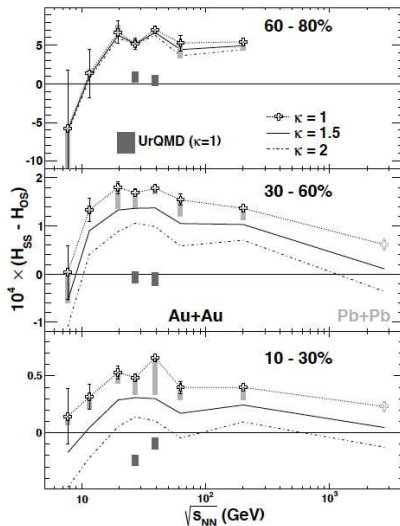
Photons from magnetic field
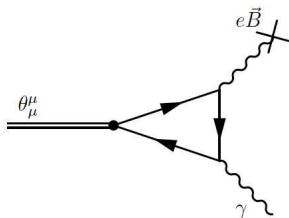
- ► Trace anomaly converts energy-momentum of gluon bulk into photons
  G. Basar, D. Kharzeev, V. Skokov
  Phys. Rev. Lett. **109**, 202303 (2012)
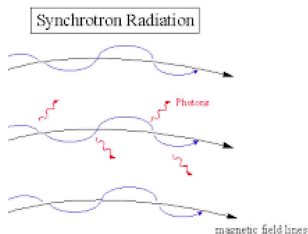
- ► Photon emission by quark synchrotron radiation
  K. Tuchin, Phys. Rev. C **91**, 014902 (2015)

Photon production from gluon fusion
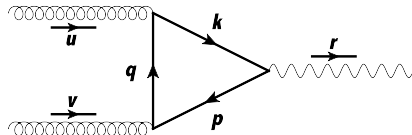
(a) *(b)*
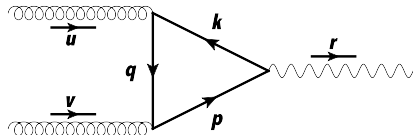
▶ Gluons are far more abundant than quarks at early times

▶ Largest magnetic field intensities and largest temperatures at early times of the collision

▶ Diagrams have same relative sign in the presence of magnetic field

Fermion propagator in magnetic field

The fermion propagator in coordinate space cannot longer be written as a simple Fourier transform of a momentum propagator

$$S(x, x') = \Phi(x, x') \int \frac{d^4 p}{(2\pi)^4} e^{-ip \cdot (x - x')} S(p)$$

where

$$\Phi(x, x') = \exp \left\{ i q_f \int_{x'}^{x} d\xi^\mu \left[A_\mu + \frac{1}{2} F_{\mu\nu} (\xi - x')^\nu \right] \right\}$$

is called the *phase factor*

Matrix element

$$
\begin{aligned}
\mathcal{M}^{(a)} &= -\int d^4x \int d^4y \int d^4z \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \int \frac{d^4k}{(2\pi)^4} \\
&\times\; e^{-ip\cdot(y-x)} e^{-iq\cdot(z-y)} e^{-ik\cdot(x-z)} e^{-iu\cdot z} e^{-iv\cdot y} e^{ir\cdot x} \\
&\times\; \mathrm{Tr}\left[iq_f\gamma_\mu iS(k) ig\gamma_\alpha t^c iS(q) ig\gamma_\nu t^d iS(p) \right] \\
&\times\; \Phi(x,y)\Phi(y,z)\Phi(z,x)\epsilon^{*\mu}(\lambda_r)\epsilon^\alpha(\lambda_u)\epsilon^\nu(\lambda_v).
\end{aligned}
$$

Fermion propagator in magnetic field: Intense field $\Longrightarrow$ Lowest Landau Level

The piece of the propagator $S(p)$ in momentum-space

$$iS(p) = \int_0^\infty \frac{ds}{\cos(q_f Bs)} e^{is(p_\parallel^2 - p_\perp^2 \frac{\tan(q_f Bs)}{q_f Bs} - m_f^2 + i\epsilon)}$$

$$\times \left[(\cos(q_f Bs) + \gamma_1 \gamma_2 \sin(q_f Bs))(m_f + \slashed{p}_\parallel) - \frac{\slashed{p}_\perp}{\cos(q_f Bs)} \right]$$

$$\xrightarrow{LLL} 2ie^{-\frac{p_\perp^2}{q_f B}} \frac{(\slashed{p}_\parallel + m_f)}{p_\parallel^2 - m_f^2} \left[\frac{1 - i\gamma_1 \gamma_2}{2} \right]$$

The operator

$$\mathcal{O}_\parallel = [1 - i\gamma_1 \gamma_2]/2$$

projects onto the longitudinal space. Therefore the **matrix element can be factorized into a product of transverse and longitudinal pieces**

Matrix element fractorizes into product of transverse and longitudinal pieces

$$
\begin{aligned}
\mathcal{M}^{(a)} &= (2\pi)^4 \delta^4(r - v - u) \mathcal{M}^{(a)}_{\perp} \mathcal{M}^{(a)}_{\parallel} \\
\mathcal{M}^{(a)}_{\perp} &= \left(\frac{4\pi}{q_f B}\right)^2 \int \frac{d^2 p_{\perp}}{(2\pi)^2} \int \frac{d^2 q_{\perp}}{(2\pi)^2} \int \frac{d^2 k_{\perp}}{(2\pi)^2} \\
&\times\ e^{-\frac{k_{\perp}^2}{q_f B}} e^{-\frac{q_{\perp}^2}{q_f B}} e^{-\frac{p_{\perp}^2}{q_f B}} \prod_{i,j=1,2} e^{i\frac{2}{q_f B}\epsilon_{ij}(q-k+u)_i(q-p-v)_j} \\
&= \left(\frac{q_f B}{12\pi}\right) e^{-\frac{(u+v)_{\perp}^2}{3 q_f B}}, \\
\mathcal{M}^{(a)}_{\parallel} &= -8 \left(\frac{q_f g^2 \delta^{cd}}{2}\right) \int \frac{d^2 p_{\parallel}}{(2\pi)^2} \int \frac{d^2 q_{\parallel}}{(2\pi)^2} \int \frac{d^2 k_{\parallel}}{(2\pi)^2} \\
&\times\ (2\pi)^4 \delta^2 \left[(q - k + u)_{\parallel}\right] \delta^2 \left[(q - p - v)_{\parallel}\right] \epsilon^{*\mu}(\lambda_r) \\
&\times\ \frac{\text{Tr}\left[\gamma_\mu \not{k}_{\parallel} \mathcal{O}_{\parallel} \gamma_\alpha \not{q}_{\parallel} \mathcal{O}_{\parallel} \gamma_\nu \not{p}_{\parallel} \mathcal{O}_{\parallel}\right]}{k_{\parallel}^2 q_{\parallel}^2 p_{\parallel}^2} \epsilon^{\alpha}(\lambda_u) \epsilon^{\nu}(\lambda_v)
\end{aligned}
$$

Early stages, gluons more abundant, quarks don't thermalize

- Hierarchy of energy scales $\sqrt{eB} > T > m$
- Early stages gluons far more abundant than quarks
- Assume quarks do not yet thermalize.
- $m_f = 0$ since in the absence of thermal corrections, the light-quark vacuum masses are negligible.
- The trace contains the product of up to twelve gamma matrices. Upon squaring and summing over polarizations, only a small piece survives

$$
\begin{aligned}
\text{Tr}\left[\gamma_\mu \not{k}_\| \mathcal{O}_\| \gamma_\alpha \not{q}_\| \mathcal{O}_\| \gamma_\nu \not{p}_\| \mathcal{O}_\|\right] \longrightarrow \quad & k_{\|\nu}(p_{\|\mu} q_{\|\alpha} - p_{\|\alpha} q_{\|\mu}) \\
+\ & k_{\|\mu}(p_{\|\nu} q_{\|\alpha} + p_{\|\alpha} q_{\|\nu}) \\
+\ & k_{\|\alpha}(p_{\|\nu} q_{\|\mu} - p_{\|\mu} q_{\|\nu})
\end{aligned}
$$

Kinematical simplifications

- For photons emitted at mid-rapidity, **momentum components along the reaction plane are small.**
- Reaction plane is perpendicular to the magnetic field then $r_\perp = (u + v)_\perp \simeq 0$.
- Focus on photons with small momentum $r_3 = (v + u)_3 \simeq 0$.
- Focus on describing emission of real photons $r^2 = (u + v)^2 = 0$.
- The main thermal effect on low momentum gluons is the development of a **thermal mass** $m_g \sim gT$.
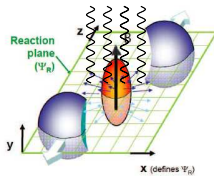
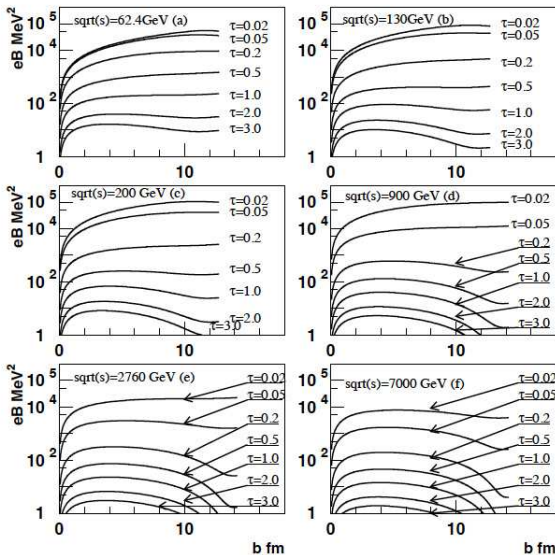Photon yield $m_f = 0$, thermal gluons, low p_t photons

$$\frac{r_0 dN}{d^3 r} = \frac{1}{2(2\pi)^3} \int \frac{d^3 u}{2u_0 (2\pi)^3} \int \frac{d^3 v}{2v_0 (2\pi)^3}$$
$$\times \sum_{\text{pol}, f} |\mathcal{M}|^2 \, n(u_0) n(v_0)$$

$$\frac{1}{2\pi N r_t dr_t} = \frac{\left[\left(\frac{1}{3}\right)^4 e^{-2\frac{v_0^2 r_t^2}{eB}} + \left(\frac{2}{3}\right)^4 e^{-\frac{v_0^2 r_t^2}{eB}} \right] \frac{I(r_t/T)}{2\pi}}{\sqrt{3\pi eB/2} \left[\left(\frac{2}{3}\right)^{9/2} + \left(\frac{1}{3}\right)^{9/2} \right] \int_0^\infty dr_t I(r_t/T)}$$

$$I(z; \lambda) \equiv \int_0^z \frac{dx x^2 n\left(\sqrt{(z+x)^2 - (2x)^2}\right) n(x)}{\left(\sqrt{x^2 + \lambda^2}\right) \left(\sqrt{(z+x)^2 - (2x)^2 + \lambda^2}\right)}$$
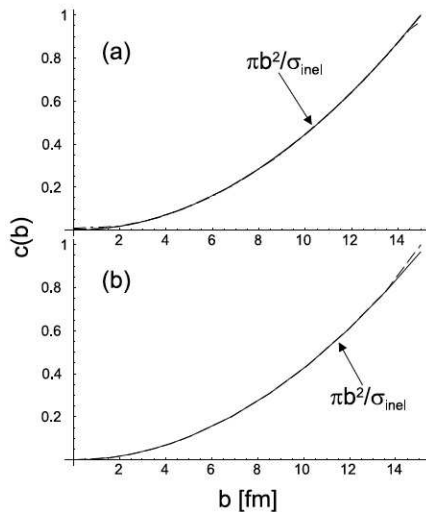
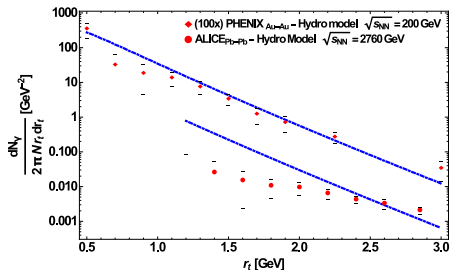# Magnetic field strength with time and impact parameter
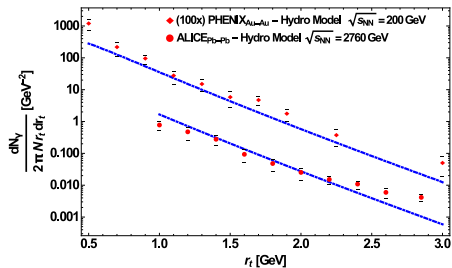
Centrality vs. impact parameter

W. Broniowski, W. Florkowski, Phys. Rev. **C** 65, 024905 (2002)

Excess photon yield from magnetic field induced gluon fusion compared to McGuil hydro

A.A., J. Castaño-Yepes, C. A. Dominguez, L. Hernández, arXiv:1604.02713

- $T = 300$ MeV for $\sqrt{s_{NN}} = 200$ GeV (RHIC)

- $T = 350$ MeV for $\sqrt{s_{NN}} = 2.76$ TeV (LHC)

- $g = 1$

- $0.5 \times 10^4 < eB/(\text{MeV})^2 < 10^5$ for RHIC

- $eB/(\text{MeV})^2 \simeq 10^4$ for LHC

Conclusions

- Magnetic fields originate observable phenomena in heavy-ion collisions
- Magnetic field induce processes otherwise now allowed such as emission of photons from gluon fusion
- Size of excess yield can be accounted for using reasonable values for eB, T and g.
- Magnetic fields naturally induce asymmetry (v_2).
- v_3 seems to be better described by models without magnetic field than v_2.